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A Study of General Education Astronomy Students' Understandings of Cosmology. Part IV. Common Difficulties Students Experience with Cosmology

Colin S. Wallace

Center for Astronomy Education (CAE), Steward Observatory, University of Arizona, Tucson, Arizona 85721

Edward E. Prather

Center for Astronomy Education (CAE), Steward Observatory, University of Arizona, Tucson, Arizona 85721

Douglas K. Duncan

Department of Astrophysical and Planetary Sciences, University of Colorado at Boulder, Boulder, Colorado 80309

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Abstract

This is our fourth paper in our five paper series describing our national study of general education astronomy students' conceptual and reasoning difficulties with cosmology. While previous papers in this series focused on the processes by which we collected and quantitatively analyzed our data, this paper presents the most common pre-instruction conceptual and reasoning difficulties identified from our qualitative analysis of students' written responses. We discuss students' naïve ideas about the expansion and evolution of the universe, the Big Bang, interpreting Hubble plots, and the evidence for dark matter in spiral galaxies.

1. INTRODUCTION

This is the fourth paper in a five paper series describing one of the first large-scale, systematic studies of general education introductory astronomy (hereafter, Astro 101) students' conceptual and reasoning difficulties with cosmology. Previous papers in this series reported on the process by which we designed and validated four surveys (Forms A–D) used to assess students' conceptual cosmology knowledge (Wallace, Prather, and Duncan 2011a, aka “Paper 1”), our classical test theory analysis of students' responses (Wallace, Prather, and Duncan 2011b, aka “Paper 2”), and our item response theory analysis of students' responses (Wallace, Prather, and Duncan 2012a, aka “Paper 3”). These papers provide the foundation for our research methodology and the validity and reliability of our investigation. In this paper, we describe Astro 101 students' most common conceptual and reasoning difficulties identified from our qualitative analysis of students' written responses.

The cognitive perspective on learning emphasizes the importance of understanding students' pre-instruction ideas. One of the primary findings of cognitive research is that students do not enter the classroom as *tabula rasa*; the knowledge, intuitions, and beliefs they bring with them exert complex and profound influences over what they learn. Furthermore, when teachers fail to account for students' prior knowledge or reasoning abilities, any learning that occurs is frequently ephemeral and superficial. The scientifically incorrect knowledge, intuitions, and beliefs that students have and use to organize and interpret information are often impervious to change from traditional, lecture-based instruction (Carey 1988; diSessa 1993; Elby 2001; McDermott 1991; Minstrell 1992; NRC 2000; Posner *et al.* 1982; Redish 1994; Strike and Posner 1992; Vosniadou 1994; von Glasersfeld 1989). If we want students to effectively learn cosmology (or any other astronomy topic for that matter), then our instruction must be informed by the ideas students bring to the classroom.

For our study, we administered four conceptual cosmology surveys to a total of 2318 students pre-instruction, representing 13 different classes. 501 pre-instruction responses came from students enrolled in courses taught in the fall 2009, 1215 came from the spring 2010, and 602 came from the fall 2010 (see Paper 1 for more demographic details). We will provide an overview of the most common incorrect ideas students bring to the Astro 101 classroom. We support our interpretations with survey data from the fall 2009, spring 2010, and fall 2010 semesters throughout the paper. We often report our data in the form X/Y/Z%, where X, Y, and Z refer to the percent of students who expressed a given idea in the fall 2009, spring 2010, and fall 2010 semesters, respectively. We calculated these percentages based on the number of students from a given semester who received a corresponding reasoning element code from our scoring rubrics. See Paper 2 for a description and an example of the scoring rubrics.

Sections 2–4 of this paper focus on describing the breadth of student pre-instruction responses. Specifically, Section 2 describes student ideas about the expansion and evolution of the universe, Section 3 examines students’ difficulties interpreting Hubble plots, and Section 4 covers students’ responses to questions about the evidence for dark matter in spiral galaxies. Section 5 summarizes this paper.

2. THE EXPANSION AND EVOLUTION OF THE UNIVERSE

Modern cosmology stems from a central idea that the universe has expanded and cooled over time from an initial hot, dense state (all of which are key aspects of the Big Bang Theory). Yet many Astro 101 students seem to possess alternative ideas about the meaning of terms such as “expansion” and “the Big Bang.” In this section, we detail some of the most common ideas students expressed about these topics.

Prior studies indicate that many people are unaware that the universe is expanding (Lightman and Miller 1989; Lightman, Miller, and Leadbeater 1987; Prather, Slater, and Offerdahl 2002). Our data add further support to this conclusion. Only 18/32/27% of students pre-instruction explicitly talked about the universe getting bigger when asked to describe what the “expansion of the universe” means. Furthermore, a sizeable minority flat out denied that it was physically growing; these students claimed that the “expansion of the universe” is simply a metaphor for how our knowledge of the universe increases over time (21/30/12%) and/or for how new objects form over time (16/14/15%). For example, one student wrote the following:

“I don’t think that it is acculuy [*sic*] expanding in a physical sense, but instead our knowledge of the unifers [*sic*] and the areas that we have discovered is expanding with an increase in technology and investments in sciens [*sic*].”

Spelling mistakes aside, this response is typical of many students’ ideas about the expansion of the universe.

Few students explicitly connected the beginning of expansion to the Big Bang. A large percentage (34/46/46%) of students claimed that the Big Bang marked the beginning of the universe and 12/10/19% of students described the Big Bang as the beginning of expansion. Some students (16/22/10%) instead claimed it was the beginning of something smaller than the universe, such as the beginning of Earth or the Solar System. This is consistent with the claims of previous studies (Prather, Slater, and Offerdahl 2002; Simonelli and Pilachowski 2003). Other students (8/10/2%) think the Big Bang refers to an event that happened to Earth or some other astronomical body. For instance, one student wrote:

“‘the big bang theory’ is when an asteroid that was headed toward earth struck the earth and every thing [*sic*] that was alive died—then as time went on things started growing and living again.”

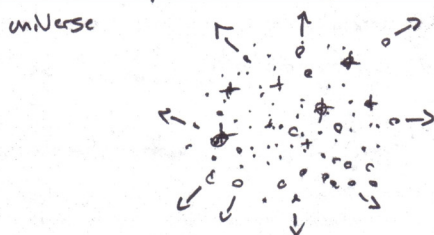
By far the most common pre-instruction description of the Big Bang was that it was an explosion (53/52/56%)—a description that many astronomers find to be a very misleading and inaccurate analogy for the Big Bang. A further 32/28/38% of students talk about matter existing before the Big Bang. Taken together, these results imply that many—perhaps even a majority of—Astro 101 students conceive of the Big Bang as an explosion of pre-existing matter into empty space. These results are consistent with the findings of Prather, Slater, and Offerdahl (2002).

Given that many students believe in an early universe composed of pre-existing matter and empty space, we should expect students to have conceptually complex ideas about whether the universe has a center or an edge.

7/23/30% of students said that the universe has a center and the center is where the Big Bang happened and/or where the universe began and/or where everything is expanding from. Others (15/12/16%) say that because everything in the universe is constantly in motion, the location of the center continually changes. With regard to the idea of an edge, we found that many students reject the idea of an edge where the entire universe and all of existence come to an end; however, many (36/34/51%) believe the universe has an edge in the sense that the distribution of galaxies eventually ends, leaving only empty space. Figure 1 shows the four responses of one student

Explain, in as much detail as possible, what astronomers mean when they say "the universe is expanding." Provide a drawing if possible to help illustrate your thinking.

When astronomers say the universe is expanding they are referencing that all stars and planets are moving out away from a central area in the universe



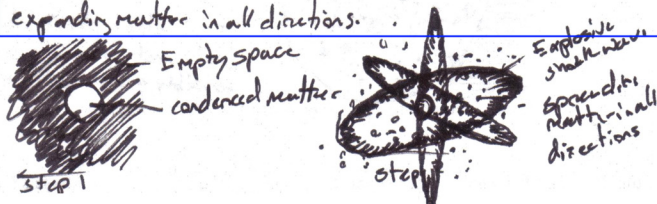
→ indicates movement of stars

→ indicates movement of stars

When astronomers say the universe is expanding they are referencing that all stars and planets are moving out away from a central area in the universe

Explain, in as much detail as possible, what astronomers mean by the "Big Bang Theory." Provide a drawing if possible to help illustrate your thinking.

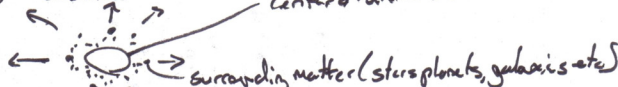
The big bang theory is meant to explain the creation of the universe as we know it today. It is based on the observations of stars moving away from us and a central part of the universe. The big bang theory basically states that all matter was condensed to a central location in the universe which then exploded expanding matter in all directions.



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If you could travel to any location in the universe, could you ever see the center of the universe? Explain your reasoning and provide a drawing if possible to help illustrate your thinking.

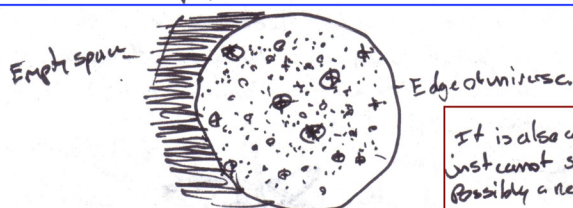
Yes, you would have to find the area in which everything, stars, matter, etc. is moving away from that central location. Also since there was no other resistance there would be no force allowing all matter to spread evenly, thus all ends would be equal distance from each other.



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If you could travel to any location in the universe, could you go to a place where there would be no galaxies in front of you? Explain your reasoning and provide a drawing if possible to help illustrate your thinking.

Yes you could, if you were to travel to literally the edge of the universe you would only see emptiness.



It is also a possibility that we just cannot see past a certain point, possibly a new type of matter.

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Figure 1. One student's responses to several items that elicit apparently widespread ideas about expansion and the Big Bang. The typed text reproduces the student's written responses verbatim.

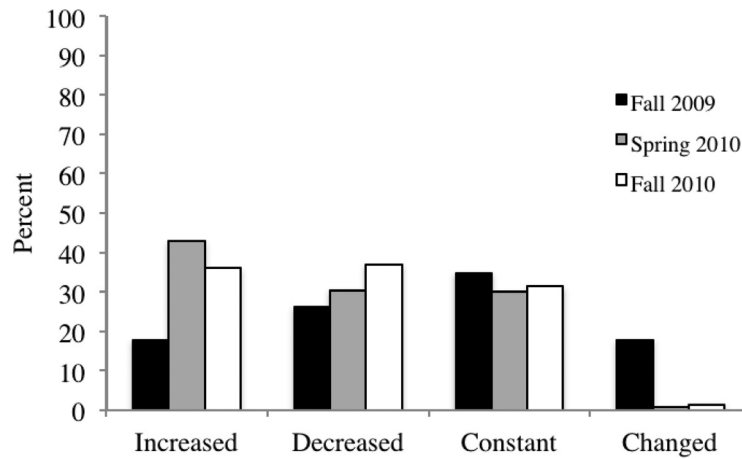


Figure 2. Percent of students who said the temperature of the universe increased, decreased, remained constant, or changed over time. Black bars represent responses from the fall 2009, gray bars from the spring 2010, and white bars from the fall 2010. The answer is “decreased.”

to items, all of which are on Form B, given in the fall 2009. His responses give an especially clear insight into this particular student’s belief about expansion and the Big Bang.

Finally, students are largely unaware, pre-instruction, of how certain physical quantities, such as the temperature and density of the universe, have changed as a result of the expansion of the universe. Consider students’ ideas about the temperature of the universe, which has decreased over time. Figure 2 shows the percent of students who think the temperature of the universe has gone up, gone down, or remained constant over time. Figure 2 also includes a fourth category—“changed”—for those students who said the temperature changed but did not specify a direction. Due to a change in how we worded the question, the percent of students falling into this category dropped dramatically after the fall 2009 semester. There is no consensus on whether and how the temperature has changed. Regardless of their answer, most students justified their choice by talking about the births, lives, and deaths of planets, stars, and galaxies. For example, of those students who said the temperature increased, 27/58/32% talked about changes during the life (lives) of a planet(s). Here is one representative response:

“I think the temperature has increased for the universe because I know on Earth the glaciers were melting faster when I went to Alaska a few years ago.”

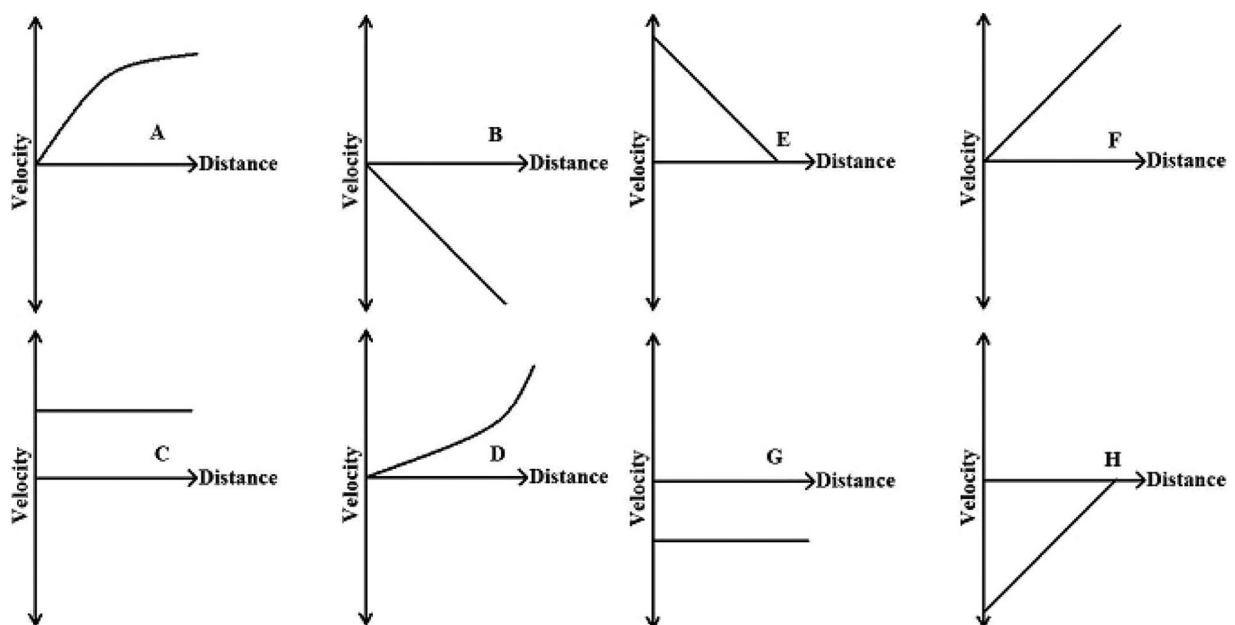


Figure 3. The bank of eight Hubble plots from which students selected their answers to Items 1–4 on Form A.

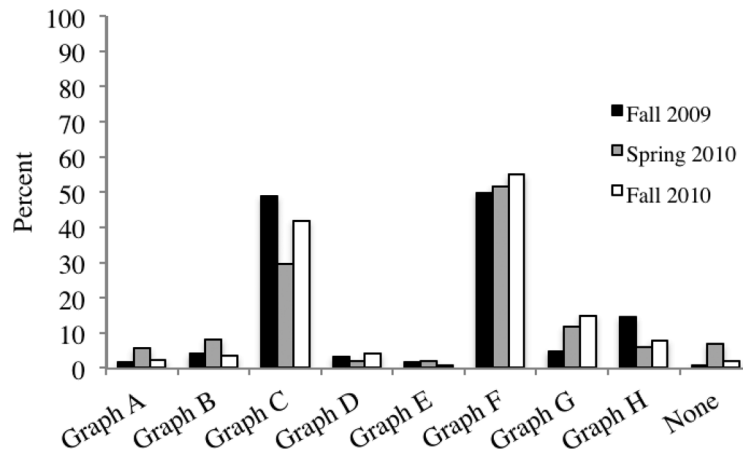


Figure 4. Percent of students who, pre-instruction, chose each graph for Form A, Item 1: Which graph or graph(s), if any, show a universe that is expanding at a constant rate? Black bars represent responses from the fall 2009, gray bars from the spring 2010, and white bars from the fall 2010. The correct answer is Graph F.

To take another example, 16/14/19% of students who said the temperature remained constant did so because they believe competing effects cancel out. Here is one response that falls into this category:

“I think the temperature of the universe has probably stayed the same because there is a lot going on and even though stars die, other ones form so it all evens out.”

These responses show that students connect changes in the temperature of the universe to cosmically insignificant changes to constituents of the universe.

3. HUBBLE PLOTS

As noted in Paper 1, we suspected many students struggle to read and interpret Hubble plots. This hypothesis was primarily based on prior studies of students’ difficulties with graph interpretation and kinematic quantities (McDermott, Rosenquist, and van Zee 1987; Trowbridge and McDermott 1980, 1981). Our hypothesis is supported by the survey responses we received from Astro 101 students.

For example, Items 1–4 of Form A of our surveys asked students to select one or more of the possible Hubble plots shown in Figure 3. Item 1 asked which Hubble plot corresponds to a universe expanding at a constant rate, Item 2 asked about a universe contracting at a constant rate, Item 3 asked about a universe expanding at an accelerating rate, and Item 4 asked about a universe expanding at a decelerating rate. The correct answers are

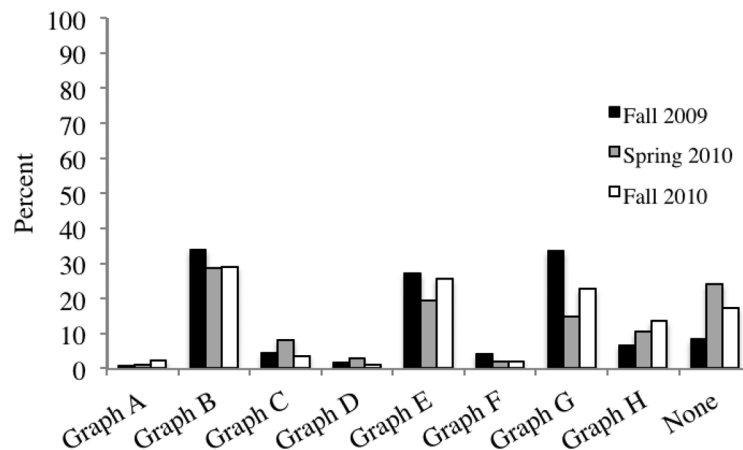


Figure 5. Percent of students who, pre-instruction, chose each graph for Form A, Item 2: Which graph or graph(s), if any, show a universe that is contracting at a constant rate? Black bars represent responses from the fall 2009, gray bars from the spring 2010, and white bars from the fall 2010. The correct answer is Graph B.

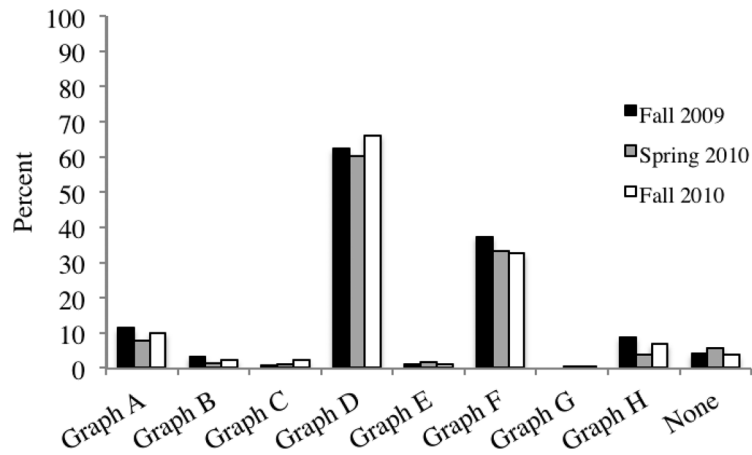


Figure 6. Percent of students who, pre-instruction, chose each graph for Form A, Item 3: Which graph or graph(s), if any, show a universe that is expanding at a faster and faster rate over time? Black bars represent responses from the fall 2009, gray bars from the spring 2010, and white bars from the fall 2010. The correct answer is Graph A.

graphs F, B, A, and D, respectively. The distributions of students' answers are shown in Figures 4–7. Note that the percentages in Figures 4–7 do not sum to 100% since students were free to choose more than one graph. Also note that simply selecting the correct answer was insufficient for a student to earn full credit on any of these items; they also had to provide complete and correct justifications for their selections. See Papers 2, 3, and 5 for analyses of the correctness of students' responses.

Figure 4 shows that Graphs C and F were the most popular choices for Item 1 pre-instruction. The overwhelming majority (74/60/68%) of students who selected Graph C provide responses indicating they did so because the graph shows a constant velocity. These results suggest that students who select Graph C do so because they equate “expansion at a constant rate” with “constant velocity.”

Those who selected Graph F for Item 1 frequently discussed relevant features of the graph. For example, 22/25/32% said Graph F shows the velocity increasing, 31/25/34% said it shows the distance increasing, and 15/8/10% said it has a constant slope. However, few students (3/3/5%) put all of these observations together to form a complete and correct justification for choosing Graph F.

For Item 2, the most frequently selected graphs were B, E, and G. As was often the case for students who chose Graph F for Item 1, students who chose Graph B for Item 2 often highlighted relevant features of the graph but failed to combine their knowledge of those features into a complete and correct justification (no student in our entire sample provided complete and correct reasoning pre-instruction). Students who selected Graphs B and E tended to focus on the fact that some aspect of the graph was decreasing or negative. For example, 57/43/23%

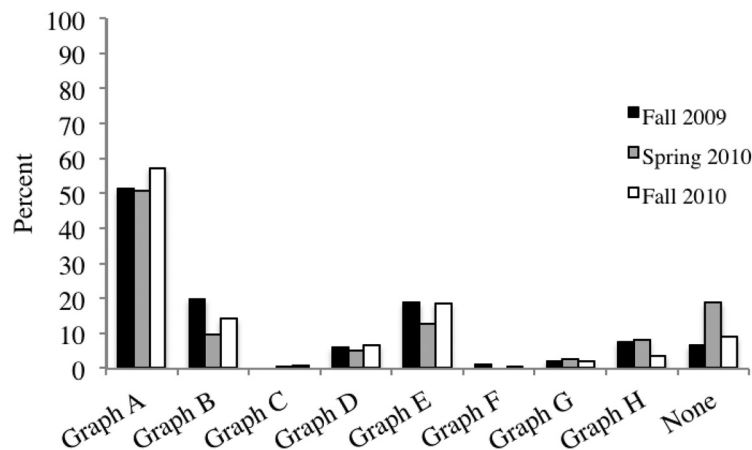


Figure 7. Percent of students who, pre-instruction, chose each graph for Form A, Item 4: Which graph or graph(s), if any, show a universe that is expanding at a slower and slower rate over time? Black bars represent responses from the fall 2009, gray bars from the spring 2010, and white bars from the fall 2010. The correct answer is Graph D.

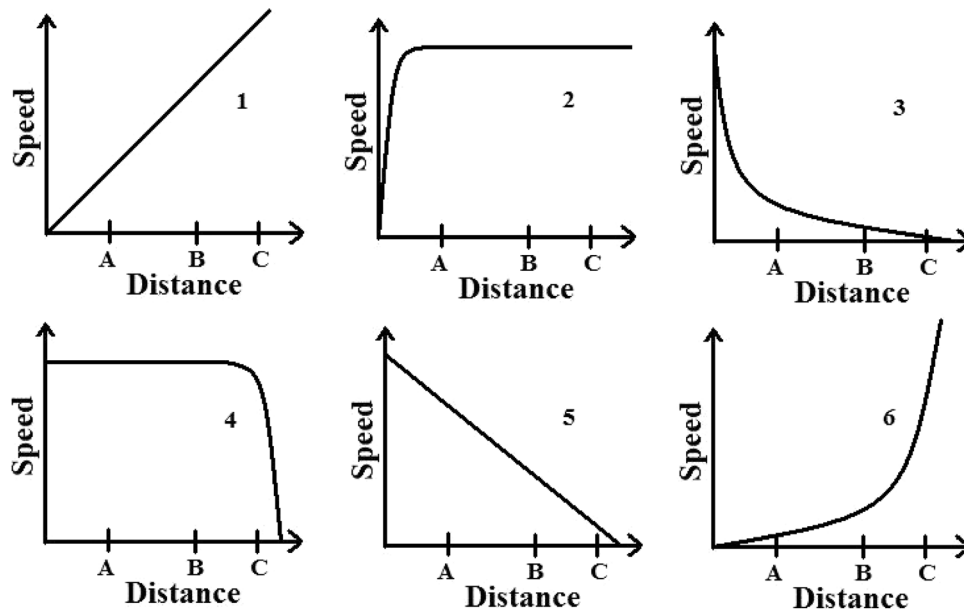


Figure 8. The bank of six rotation curves from which students selected their answers on Form D.

of students chose B because “it” or “the velocity” is decreasing. 28/45/28% of students who chose Graph E used a similar reasoning. What about those who selected Graph G? Like those who chose Graph C for Item 1, these students typically focused on velocity: 48/39/51% said the velocity is constant, while 33/41/45% said the velocity is negative. Overall, the reasoning patterns of students answering Item 2 were similar to those of Item 1.

Most students either chose Graph D or Graph F as their answer for Item 3, even though Graph A is the correct answer. Not surprisingly, most students in their responses to Item 4 said that Graph A represents a universe expanding at a slower and slower rate over time. For example, 68/41/30% of students in response to Item 3 said Graph D shows a universe expanding at a faster and faster rate over time because it shows the velocity or the line increasing. Similarly, the 69/67/52% of students who selected Graph F in response to Item 3 stated that this graph shows the velocity increasing. Students responding with Graph A to Item 4 typically provided responses stating that the line levels off with increasing distance. Taken together, students’ responses to Items 3 and 4 indicate that, pre-instruction, many students made one of the common graph interpretation errors noted by [McDermott, Rosenquist, and van Zee \(1987\)](#): They answer these items by incorrectly referring to the height of the line when the slope of the line is the relevant quantity. To choose the correct graph, a student must recognize that the expansion rate is highest where the slope is steepest. Furthermore, the student must read large distances

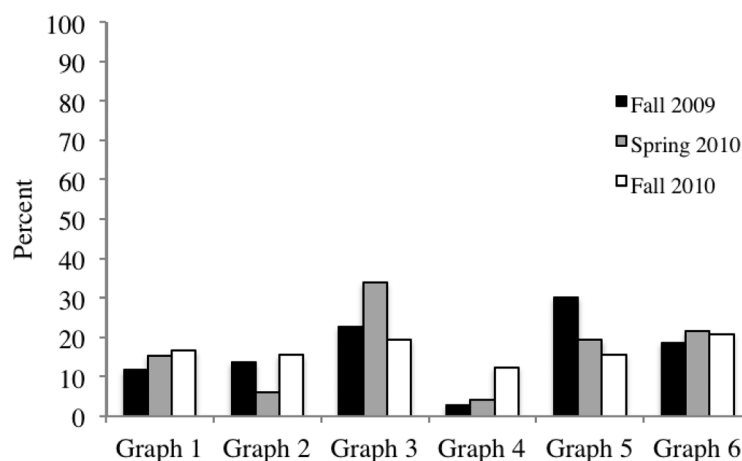


Figure 9. Percent of students who, pre-instruction, chose each graph for a spiral galaxy’s rotation curve. Black bars represent responses from the fall 2009, gray bars from the spring 2010, and white bars from the fall 2010. The correct answer is Graph 2.

on a Hubble plot as corresponding to times far in the past. When answering Items 3 and 4, no student in any semester took into account the fact that the farther one looks into space the further back in time one sees.

4. DARK MATTER IN SPIRAL GALAXIES

Form D probed students' knowledge about the evidence for dark matter in spiral galaxies. When constructing Form D, we were careful to write items that never contained the words "dark matter." Instead, we had items that referred to rotation curves and the distribution of matter. In this way, we hoped to see whether or not students, on their own, would introduce the idea of dark matter in their answers.

Pre-instruction, almost no student said anything about dark matter. Unfortunately, our versions of Form D from the fall 2009 and spring 2010 semesters contained only four items, one of which was removed during analysis because it was deemed conceptually problematic from an astrophysical standpoint. This limited our ability to infer much about students' difficulties from these semesters. Thus, the results reported here are predominantly taken from the responses we received in the fall 2010.

On all three semesters' versions of Form D, we asked students to choose the correct rotation curve from a bank of six rotation curves (Figure 8) for a spiral galaxy. We were careful to define the term "rotation curve" in the item and interviews with students revealed that the term was not commonly misunderstood. Previous research indicates that some students confuse the definitions of "galaxy" and "solar system" (Hayes *et al.* 2011), but our interviews and written responses did not reveal this particular difficulty. Figure 9 shows the distribution of students' selections for all three semesters (fall 2009, spring 2010, and fall 2010). Note that while no single graph attracted a majority of students, the correct answer (Graph 2) was often one of the least popular choices.

For the fall 2010 version of the Form D, we added several items that asked students to think about the rotation curve for and distribution of matter in a solar system. Figure 10 shows the distribution of students' choices (from the same bank as Figure 8) for which graph represents the rotation curve of a solar system. Once again, most students did not select the correct answer (Graph 3). The reasoning provided by students to support their graph choices regarding the rotation curves of galaxies and solar systems did not highlight any particular reasoning difficulties held by a significant number of students.

We next asked students to rank the orbital speeds of the planets shown at different distances (labeled A, B, and C in Figure 8). We also asked students to rank the orbital speeds of stars shown at different distances (also using Figure 8). Students' reasons for their rankings provide us with intriguing insights into Astro 101 students' ideas about motion. Planet A was most commonly ranked as the fastest moving planet, and Star A was most commonly ranked as the fastest moving star. Students choosing Planet A as the fastest moving either provided no explanation (14%) or attributed the planets' motion to its shorter orbital path (14%) or shorter orbital period (4%). Students choosing Star A as the fastest moving either provided no explanation (7%) or attributed the planets' motion to its shorter orbital path (6%) or shorter orbital period (2%).

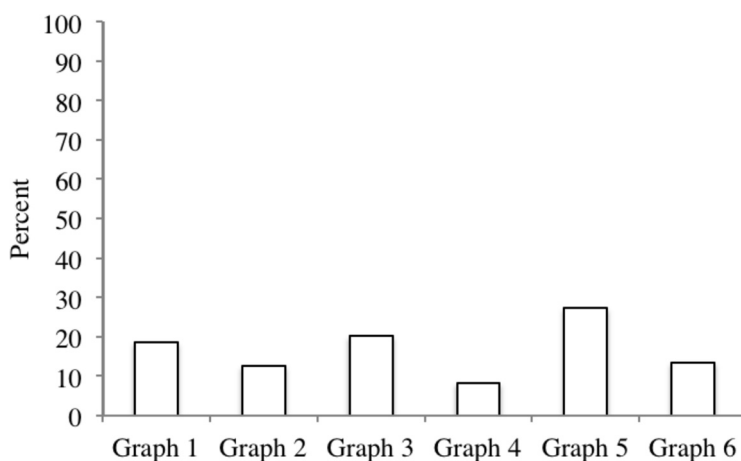


Figure 10. Percent of students who, pre-instruction, chose each graph for a solar system's rotation curve in the fall 2010. The correct answer is Graph 3.

Frank, Kanim, and Gomez (2008) propose that students' ideas about motion are assembled from in-the-moment, context-dependent activations of one or more cognitive resources. Their list of resources relating to students' intuitions about motion bears some similarities with the student reasoning in this study. While our data does not prove students are drawing on fine-grained cognitive resources to construct their answers, we think a "resources" perspective may be the most productive way to understand students' responses in this context, since we doubt students have robust misconceptions about rotation curves.

During the fall 2010, we also asked students where most of the matter were located in both the solar system and the galaxy. 50% said most of the solar system's mass is concentrated in the Sun, and 60% said most of the galaxy's mass is concentrated in its center. On the final question of the survey, 54% of students revealed that they thought stars orbiting the galaxy have analogous motions to planets orbiting the Sun. These results underscore an important point: Students may automatically assume everything they learn about the dynamics of the Solar System (which they typically cover long before they reach lessons on cosmology) automatically apply to galaxies. While there are certainly common physical principles governing both types of systems, students may miss key observational differences and their consequences if they never encounter instructional strategies that have been informed by research into their naïve ideas (see Wallace, Prather, and Duncan 2012b, aka 'Paper 5').

5. SUMMARY

In this paper, we described several common naïve ideas Astro 101 students bring to their classrooms. Our study uncovered a myriad of conceptual and reasoning difficulties on the expansion and evolution of the universe, the Big Bang, interpreting Hubble plots, and the evidence for dark matter in spiral galaxies.

This paper likely raises an important question in the minds of Astro 101 instructors: "What can we do to help our students overcome these difficulties?" After all, cognitive research demonstrates that effective instruction must account for students' pre-existing knowledge. In Paper 5, we describe the design and validation of a new suite of cosmology *Lecture-Tutorials*. These new *Lecture-Tutorials* are designed using the same principles as the previously successful *Lecture-Tutorials for Introductory Astronomy* (Prather *et al.* 2008). While we do not claim a *Lecture-Tutorial* approach is the only way an instructor can address student difficulties, it is an approach which research suggests can be highly effective (Prather *et al.* 2004; LoPresto and Murrell 2009; Paper 5).

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